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Frank C. Jones

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Goddard Space Flight Center
Greenbelt, Maryland 20771

COSMIC-RAY MODULATION AND THE ANOMALOUS COMPONENT

Frank C. Jones

Laboratory for High Energy Astrophysics
NASA/Goddard Space Flight Center
Greenbelt, MD 20771

Introduction

This review is concerned with advances in Cosmic-Ray Modulation observation and theory and in the study of the anomalous component of the cosmic radiation. It concentrates primarily on advances made in American research and reported in the open literature during the years 1979-1982. This rule is, of course, not rigidly adhered to; certain works that are intimately related to the subject under discussion are cited even though they may lie outside of the above mentioned bounds.

Since the last report in this series there have been two International Cosmic Ray Conferences, in Kyoto in 1979, and in Paris in 1981. A great number of papers that are relevant to our subject were presented at both of these conferences. I have, therefore, cited freely from the proceedings of these conferences with one exception; If I found that a conference paper was subsequently published, by the same authors, in unchanged or expanded form in the open literature, I considered the conference paper to be a "preliminary report" and have cited the final paper instead.

I have broken down the bibliography into several categories making it a bit easier for the reader to concentrate on areas of special interest. A paper that bears on more than one of the categories will be found under each category to which it relates. Since theoretical papers usually deal with a rather narrowly defined area while experimental results can bear on a variety of issues the latter are more likely than the former to be found more than once in the bibiography.

Microscopic Diffusion Theory

The field of microscopic diffusion theory has remained relatively quiet during the last four years. No clear cut answer has yet emerged as to why the scattering mean free path (MFP) λ for low energy particles (rigidity < 1 GeV) appears to be somewhat longer than theory predicts, but the two values do seem to be converging somewhat.

The primary tool for investigating the scattering of particles in the heliospheric magnetic field remains the observation of solar particle events. Since this is in the area of a different review this could pose a territorial problem were it not for the fact that Palmer (1982) has published an excellent review of just this topic. In this paper Palmer studies the solar particle data from the point of view of what it tells us about the scattering mean free path of charged particles in the heliosphere. He argues, persuasively, that a consensus is emerging that most of the time the scattering MFP of solar particles with rigidity < 1 GeV lies in the range 0.08 to 0.3 AU. There do seem to be cases of "scatter free" propagation events but they are rare and probably represent a highly unusual state of the interplanetary magnetic field (IMF).

Goldstein (1980) produced a flat λ vs. rigidity curve by considering the role that mirroring plays in scattering particles through 90 degrees pitch angle. He pointed out that it was the fluctuations in $|B|$ that caused the large pitch angle diffusion coefficients around 90 degrees in the various non-linear theories and computer simulations. Without this effect back-scattering is difficult and larger values of λ result.

He further pointed out that the IMF is depleted in fluctuations in $|B|$; they are Alfvenic. Whereas $|\delta B_{\perp}|$ is typically $0.6|B|$, $\delta|B|$ is only ~

$0.06|B|$. Since mirroring is a non-resonant phenomenon, for those rigidities for which it is the primary cause of backscatter the MFP will be constant. Goldstein derives a value of 0.3 AU for λ, just at the top of the consensus band.

In their fundamental paper on the theory of diffusion of charged particles in random magnetic fields, Hasselman and Wibberenz (1968) included the effects of an average twist or helicity of the field on the pitch angle diffusion coefficient. They showed that it could reduce the scattering, possibly by a large amount. This fact has remained essentially forgotten until recently when Matthaeus et al. (1982) showed how to evaluate the helicity of the IMF and that it was large, approaching 100%, a great deal of the time. Goldstein and Matthaeus (1981) and Matthaeus and Goldstein (1981) also discussed its role in cosmic-ray transport theory, which could turn out to be considerable. As we shall discuss in a later section the helicity of the field can have an effect not only on the scattering of charged particles but on their drift motion as well. The prime difficulty with this approach is that the helicity of the IMF appears to be a random function of wave number, k, with essentially no correlation from one value of k to another. What all of this adds up to (in the sense of a sum over wave number) is still a bit uncertain at the present moment and we will have to wait awhile yet to see where this line of research is leading.

For awhile it appeared that one new approach was going to turn up something quite significant. Gombosi and Owens (1980) examined a model of solar particle propagation using an approach initiated by Ng and Wong (1979) in which one numerically integrates the time dependent, two dimensional Fokker-Planck equation by means of a finite difference technique. This equation describes the propagation in time, heliocentric radius and pitch

angle of particles released at $t=0$ at the surface of the Sun. The pitch angle diffusion coefficient D_0 was treated as variable parameter and related to the particle MFP λ by means of the Quasi-linear result $\lambda_r = 1.2 \cos^2 \Psi \, \ell/D_o$

After obtaining solutions to this equation they were able to fit them with a solution to the phenomenological diffusion equation but discovered a peculiar thing. No matter how large they made D_o and therefore how small λ_r should be, the value of the MFP deduced from the best fit diffusion solution never got smaller than 0.1 AU. Therefore Gombosi and Owens deduced and later (Owens and Gombosi 1981) reiterated that the diffusion equation was not a valid approximation to the full Fokker-Planck equation that described the propagation of solar particles.

Unfortunately this lead did not hold up. Palmer and Jokipii (1981) performed a Monte-Carlo simulation of the identical problem and found quite good agreement with the diffusion approximation solution. Subsequently Kota et al. (1982) reported a detailed numerical calculation in which they found excellent agreement with diffusion theory. They were also able to demonstrate that the finite grid size used by Gombosi and Owens and the particular numerical technique that they employed had subtly conspired to produce the apparent lower bound on the MFP.

Gradient and Curvature Drift

The past four years have seen a continuing high level of effort in understanding the role played in cosmic-ray modulation by drift motions of charged particles produced by the gradients and curvature of the average IMF. Jokipii and his co-workers have carried their work into the numerical modeling phase with the paper by Jokipii and Kopriva (1979). In this paper

the authors study a model of the modulation process which includes, in addition to the above mentioned drifts, a parallel diffusion coefficient $\kappa_{\parallel} = 5\times10^{21}\ P^{1/2}\beta\ cm^{2}\ S^{-1}$ and a perpendicular diffusion coefficient $\kappa_{\perp} = 0.1\times\kappa_{\parallel}$, a typical solar wind speed of 400 km/sec, and the standard Parker spiral IMF. They found that with an outer modulation boundary of 10 AU they were able to produce the observed spectrum quite well with a very low value of the radial gradient (< 5%/AU) over most of the heliosphere, increasing to very large values as the boundary is approached at about 9 AU. This only applies to the solar cycle 1969-1979; with field reversal the gradient should increase to very large values reaching about 50% at 1 AU.

Responding to the criticism that in the previous work the scattering frequency became much larger than the cyclotron frequency in the outer heliosphere, Jokipii and Davila (1981) repeated the calculation this time allowing the diffusion coefficient to vary inversely with the average magnetic field. Their results were similar to the previous ones with an increased role for diffusion as was expected. However when one examines the gradients that were produced the results look quite different; some latitude gradients changed sign in the inner heliosphere for the present cycle and cases where particles were injected only at the poles yielded radial gradients that were not always positive. This situation is complicated further by the results of Kota and Jokipii (1982). In this paper the authors show that negative latitude gradients can be produced if the equatorial neutral sheet is rippled as would be produced by a tilted, rotating magnetic dipole in the Sun. This indicates that the real situation is likely to be much more complicated than had originally been hoped.

On the purely theoretical side Isenberg and Jokipii (1979) published a paper that discussed the generality of drift motions. In this paper they

showed that for a distribution of charged particles the existence of these motions did not depend on the conditions for the validity of the guiding center approximation being fulfilled at all. All that is required is for the distribution to be "almost isotropic", this condition substituting in some way for the smooth field condition usually required. In a later paper Lee and Fisk (1981) took exception to what they felt was too sweeping a claim for the universitality of drift motions. They constructed a model of the IMF that contained twists in the field lines, suggested by the designs of such plasma machines as the stellarator, and showed that the twists prevented the drift motions from persisting over finite distances. Isenberg and Jokipii responded (1981) that they had not claimed that drifts were inevitable, simply that guiding center theory was not required and that situations where the fields underwent large fluctuations would have to be investigated in their own right.

Lee and Fisk referred to an earlier paper by Forman et al. (1974) that supposedly had shown that within the confines of quasi-linear theory only diffusion in velocity space can result from the fluctuations of the magnetic field. They, nevertheless, felt that twists such as the ones employed in their model were quite likely to exist in the IMF and have the predicted effect even though they were not treatable by Quasi-Linear theory. It should be pointed out, however, that in the paper by Forman et al. (1974) the authors explicitly limit themselves to the case where the power spectrum tensor of the magnetic fluctuations is diagonal. This precludes any description of statistical helicity such as has now been observed in the IMF by Goldstein and Matthaeus (1981). This helicity in the scattering tensor can add directly to the anti-symmetric matrix representing the effect of the average field and either reduce or enhance the drift effect depending on the relative sign of two terms. This has nothing to do with the question of the validity of quasi-

linear theory. However, if the fluctuating field is small compared to the average field (the condition for quasi-linear theory to be valid) the perturbation on the drifts will likewise be small. One would expect, therefore, that any fluctuating fields that seriously distort the drift effects would have to be at least as large as the average field itself.

Observations that have a bearing on the issue of the importance of drifts in cosmic-ray modulation are somewhat harder to come by than are theories. I believe that this is largely due to the difficulty in finding an observational phenomenon that is an unambigious indicator of drift processes at work. There have been several measurements of gradients now that the Pioneer and Voyager spacecraft are probing the outer solar system. Unfortunately, as we have seen, the theory has become somewhat ambigious on the issue of what sort of gradients, radial or latitudinal, should be observed.

Mendel and Korff (1979) reported that the changes in the electron to proton intensity ratio (e/p) observed over the last two solar cycles, 1958-1978, were 180 degrees out of phase with the predictions of early drift theory. Evenson et al. (1979) reported that the field reversal in 1969-1971 had no effect on the e/p ratio at all. The changes that were seen in this ratio were strongly correlated with qualitative changes in the electron spectrum. They were able to reproduce these changes with a simple "force field" model of solar modulation by letting the parameters change. A change in the potential ϕ and the outer modulation boundary R_B from ϕ = 560 MV, R_B = 25 AU to ϕ = 280 MV, R_B = 50 AU was sufficient to produce the observed changes in the electron spectrum and in the e/p ratio.

Newkirk and Lockwood (1981) used K-coronameter and solar wind data to determine the earth's heliomagnetic latitude during 1965 and 1975. Neutron monitor data during this time indicated a negative latitude gradient which did

not reverse with the field reversal in 1969-1971. They conclude that this is in conflict with the drift theory predictions (however, see above). Swinson and Kananen (1982), on the other hand, come to the opposite conclusion. They used neutron monitor data from Deep River and Oulu, Finland with underground muon telescope data from Bolivia, Embudo and Socorro, NM to determine the heliomagnetic latitude gradient of the cosmic ray flux. They make use of the fact that a $\underline{B} \times (\underline{\nabla}N)_{\perp}$ flux contributes to the diurnal variation a term that depends on the sign of B and on the sign of the gradient. This term adds algebraicly to the $\underline{B} \times (\underline{\nabla}N)_{\parallel}$ term in a way that allows them to be separated.

They found that there was a greater diurnal variation on the days that the local IMF was pointing away from the Sun than on days that it was pointing towards the Sun. From their analysis this implied that the latitude gradient of the cosmic rays was downward, in agreement with Newkirk and Lockwood. However, in 1971 this effect reversed indicating that the cosmic ray gradient had switched when the polarity of the solar field switched. I find this result puzzling; if the cosmic ray gradient is indeed controlled by the sign of the solar field there should be a mirror symmetry across the neutral sheet. Furthermore, if the changes in direction of the local IMF from outwards to inwards and vice versa are caused, as is believed, by the earth's crossing the neutral sheet, the sign of the cosmic ray gradient should have changed with it giving no change in the diurnal variation. There is clearly more going on here than I am able to understand at the present time.

At lower energies (including anomalous components) McKibben et al. (1979) and Bastian et al. (1981) found latitudinal gradients of a few percent per degree but varying from about -2 to + 3 percent per degree. Roelof et al. (1981) also found low energy, (> 20 MeV/nucleon) latitudinal gradients > 1 percent per degree between 1 and 5 AU, but found them to be quite time

variable. These results, coupled with the above mentioned theoretical ambiguities, make interpretation in terms of drift theory beyond my present understanding.

The difference between the solar cycles of 1954-1965 and 1966-1976 in the rigidity dependance of the modulation had been thought to be a possible indicator of the effect of solar field polarity. This difference had been seen by comparing the long term records of the neutron monitors at Climax, CO and Huancayo, Peru. Cooper and Simpson (1979) were able to show, however, that the difference between the two solar cycles could be completely understood as the result of the secular change in the earth's magnetic field and the resulting change in the cutoff rigidity at Huancayo.

Shea and Smart (1981) noted that the (anti) correlation between the Mt. Washington neutron monitor rates and the Zurich sunspot number or the geomagnetic aa index was greater for 1958-1968 than for 1969-1979. According to the drift theory proton entry into the heliosphere is via the neutral sheet during the first period and via the polar region during the latter. Jokipii (1981) investigated the effect of perturbing $\kappa_\perp$ in the vicinity of the neutral sheet and found that he could produce effects similar to those found by Shea and Smart. This would indicate that the neutral sheet does indeed play some role in the control of cosmic rays in the heliosphere.

This conclusion is strengthened by the following observation of Duggal et al. (1981b). They noted that while corotating interaction regions (CIR's) always produce geomagnetic effects when they pass, they produce changes in the cosmic-ray intensity only when they have a neutral sheet imbedded in them.

Global Modulation Theory

One of the goals of global modulation theory has been to determine the spatial variation of the diffusion coefficient to be used in the diffusion-convection equation. This effort has proceeded in various ways: by analysis of solar particle events using Pioneer 10/11 and Voyager 1/2 data out to ~ 6 AU (Hamilton 1981), by treating the radial gradient, given from measurement , as a parameter and solving the modulation equations for κ as a function of radius (Hsieh and Richter, 1981), and by a purely theoretical derivation using data on stream structure to deduce the proper wave spectrum in the presence of CIR's (Morfill et al. 1979). All of these methods have lead to similar results, the radial diffusion coefficient drops to a mimimum value in the vicinity of one AU and then rises to an asymptotic value of a few times 10^{22} cm^2 s^{-1} per sec at a radius of a few to ten AU. This would indicate that global theory and observation are not wildly out of line.

Hundhausen et al. (1980) pointed out that the total area included in solar polar coronal holes correlated positively and strongly with the cosmic-ray flux as measured by the Mt. Washington neutron monitor. They offered no theory of this correlation but noted that it demonstrated the essential three dimensional nature of solar modulation. Venkatesan et al. (1980a) suggested that this result could be understood if one remembered that a large area given over to coronal holes meant steady, well ordered solar wind with no high speed streams that produce Forbush type decreases. This would produce a positive correlation with the cosmic-ray flux.

Thomas and Gall (1982) investigated, by numerical orbit tracing, the effect of the compressed magnetic fields in CIR's on the propagation of cosmic rays. They found that particles traversed these regions of enhanced magnetic

field with difficulty and that this difficulty, coupled with the adiabatic energy loss suffered by particles trapped between these regions, could possibly account for most modulation effects. Although we shall see that CIR's are probably not the principal contributor to solar modulation this approach is probably very much on the right track.

Hatten (1980 and for a more sophisticated version see Hatten and Bowe, 1981), using a technique originated by Nagashima and Morishita (1979) who applied it to the sunspot number, studied solar flares of importance greater than one and found that they depress the cosmic-ray flux for about ten months. Then upon adding up the effects of all observed flares during solar cycle 20 (1965-1976) he was able to reproduce quite well the cosmic-ray flux that was observed. He noted, however, that during solar minimum there were variations that seemed to be correlated more with high speed streams than with solar flares (which are scarce during solar minimum). It appeared that when the effect of the solar flares was slight the residual, small effect of the average solar wind speed made itself evident in the data.

Anomalous Component

Research in this field has remained focused on the question of whether this low-energy component has its origin in a heliospheric acceleration process as proposed by Fisk et al. (1974) or comes from outside the heliosphere as suggested by McDonald et al. (1977). Central to this question is the effort to determine the charge state of the nuclei in question. The local acceleration model of Fisk et al. (1974) pictures these low-energy He, N, O, and Ne nuclei as neutral interstellar atoms that enter the heliosphere, are singly ionized by solar UV and subsequently accelerated by some plasma

process in the solar wind.

It was first noted by McKibben (1977) that the anomalous He component exhibited a short response time to changes in solar modulation, as though it had a higher rigidity than its energy would indicate if it were fully stripped. This observation led McKibben to the conclusion that the anomalous He was singly charged.

Klecker et al. used this technique to study the anomalous O component and concluded that it had a charge of less than or equal to 4. This uniform trend was broken, however, by Paizis and von Rosenvinge (1981) who performed a similar analysis on low-energy He and concluded that while it was true that this component exhibited a response to solar modulation that was anomalously fast for its energy this remained true whether one assumed that they were singly or doubly charged. They therefore asserted that this technique was incapable of addressing the question of the charge state of the anomalous component.

If the state of the anomalous component's charge remains somewhat undetermined it has become abundantly clear that this low-energy component is strongly affected by solar modulation. By 1979 it was shown that the low-energy He ions were modulated at least as much as the normal component (Bastian et al., 1979b; McKibben et al., 1979; Pyle et al., 1979) and there appeared the first report of the vanishing in 1978 of the low energy Oxygen at 1 AU (Hovestadt et al., 1979). There were also reports that the anomalous He exhibited a larger heliospheric latitude variation than did the normal component (Bastian et al., 1979a; McKibben et al., 1979). This strongly suggested that off ecliptic and perhaps solar polar effects were involved in the production of these particles.

By 1981 and the Paris Cosmic Ray Conference the anomalous component had

clearly vanished at 1 AU (Garcia-Munoz et al., 1981) but was still present with decreased radial gradient of 2-8 %/AU (McKibben et al, 1982b; Bastian et al., 1981). This contrasts with results from 1972 through 1979 which showed no change (~ 15 %/AU), while during the same period from the intensity of the anomalous component changed by a factor of ten (Webber et al., 1981). If this behavior is to be explained by conventional, spherically symmetric modulation theory it would require a radius of the outer modulation boundry of hundreds of AU's.

Such a situation is probably not the case. The reasons for saying this will be discussed later in this article after we have had a chance to review the evidence on modulation in general. At the very least we can say that the anomalous, low-energy component of the cosmic rays has its origin some place beyond ~ 23 AU, perhaps quite a bit farther. It is not distributed with spherical symmetry within the heliosphere, exhibiting a positive gradient towards the poles. This does not mean that the source of this component is not symmetric about the solar system; as we shall see the cosmic rays in general are not distributed within the solar cavity with spherical symmetry.

General Modulation Observations

As a quick glance will verify, the reference list for this section is by far the longest. Space limitations do not permit discussion of all of these papers although some have been discussed in other sections; we must select only a few themes for discussion here.

By 1981 Pioner 10 had reached a distance > 23 AU and it was clear to the experimentors on board that Forbush decreases and other modulation effects were propagating outwards with approximately the solar wind speed. Van Allen

(1979) reported a Forbush decrease that propagated with a speed of 960 km/s. The recovery period was only 22 days when it was at ~ 7 AU but by the time it reached ~ 16 AU the recovery took 150 days. However, von Rosenvinge et al. (1979) discussed this and other events of a similar nature and pointed out that several other decreases were included in this 150 day period and this time should not be considered the recovery time for one single event. Further, McDonald et al. (1981b) cited 14 cases of radially propagating shock waves associated with large solar flares. These shock waves were seen to accelerate particles over their entire lifetime.

Many parameters of cosmic-ray modulation were measured, such as its energy dependence (Venkatesan et al., 1980b; Evenson and Meyer, 1981) and the way that different species of particles are affected. Evenson et al. (1981) noted that the electron to proton (e/p) ratio decreased by a factor of 2-4 between 1965 and 1975 but held constant from 1974 to 1979 a period during which the flux changed by a factor of 4. They point out that the first period includes the solar field reversal of 1969-71. von Rosenvinge and Paizis (1981) found that low energy (<20 MeV) helium was modulated more than protons even though their rigidity was 2-4 times greater. Their answer to this puzzle was that while the protons have a spectrum proportional to energy the helium spectrum is flat. Thus adiabatic energy loss will compensate for modulation for the protons but not for the helium. They take this to be evidence for adiabatic energy loss in the solar wind.

With observation posts distributed between 1 and 23 AU it is only natural that the radial gradient has been studied. Webber and Lockwood (1981) found a radial gradient of (2.85 ∓ 0.5)%/AU between 2-23 AU for particles of nominal energy 1 GeV. They also noted that modulation effects propagated outwards at a speed of 350-500 km/s. McDonald et al. (1981a) found for 100-200

MeV/nucleon particles a gradient of 3.5%/AU between 1 and 23 AU. They found that Forbush decreases and other modulation effects propagated outwards with a speed of ~ 550 km/s. McKibben et al. (1982a, 1982b) observed for protons and helium-4 nuclei of energy >67 MeV/nucleon that the gradient went from 4.5%/AU to 1.5%/AU between 1975 and 1979. In the period 1979 to 1980 it went back up to 3%/AU. They found that time variations traveled outwards at about 400 km/s. In the papers mentioned above the gradients were computed after correcting for the "convection" effect i.e. the fact that time variations propagate outwards at a finite speed. This fact is, I believe, of some significance that I will discuss in the last section.

Comments

The following comments are based solely on my reading of the papers reviewed in this article. They are not based on any rigorous study of my own but are simply my impression of the way things seem to be going.

The anomalous component surely comes from nearby but just as surely from beyond 23 AU. The charge state is still not definite so it's still too soon to tell whether or not the source of this component is inside or outside of the heliosphere.

In microscopic diffusion theory the study of the magnetic field helicity will probably prove interesting with respect to the IMF itself - possibly with respect to cosmic ray modulation. Not much else has happened in this area in the last few years nor in my opinion is it likely to; I do not believe that the answer lies in that direction.

Gradient and curvature drifts must occur. They probably play some role in particle propagation in the heliosphere, particularly in the vicinity of

the neutral sheet; there is considerable evidence that something significant is going on there. However, I doubt that these drifts play the dominant role in cosmic-ray modulation that the original investigators envisioned for them; I believe that the cause of the 11 or 22 year cycle lies elsewhere.

As for the global picture it appears to me that a mean free path in the consensus band (~ 0.1 AU) coupled with a solar wind speed of 400-500 km/s gives a radial gradient of 3-5%/AU which is in the right ballpark. It's in the right ballpark for the steady state model which is probably a good picture of solar minimum. At solar minimum the correlation of the cosmic-ray flux and the average solar wind speed seems to appear.

It's probably a pretty good picture at other times too when the effects of convecting structures are subtracted out by shifting the times of comparison of detectors at different radii. Allowing for the propagation time of these shock waves, as the various experimentors have done, allows the underlying, steady state, gradient to manifest itself.

This steady state model, however, does not describe the variation of the cosmic-ray flux over the 11 (or 22) year solar cycle. This is most likely produced by the cumulative sweeping effects (Forbush decreases) of radially propagating shock waves. These shock waves are the ones produced by the large solar flare events that correlate well with the cosmic-ray flux until they reach an outer boundary of about 60 AU. The shock waves that are associated with CIR's produce similar effects but they seem to be much more transient, probably due to their smaller spatial extent.

It is profoundly to be hoped that four years from now we will know whether these ideas and hunches are with or without substance.

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